Oilseed Radish Effects on Soil Structure and Soil Water Relations

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ABSTRACT

Oilseed radish (*Raphanus sativus* spp. *oleifera*) reduces sugarbeet cyst nematode (*Heterodera schachtii*) populations. Fall-incorporated radish biomass may also increase the yield and quality of subsequently grown sugarbeet (*Beta vulgaris* L.) by improving soil physical and hydraulic properties. This field study determined radish effects on near-surface soil aggregate stability, water-stable aggregate size distribution, bulk density, and field-saturated water content, as well as infiltration and hydraulic conductivity measured at water supply potentials of -40, -20, and +0 mm H_2O. In 2003 and 2004 in Twin Falls, ID, radish were grown in a Portneuf silt loam (Durinodic Xeric Haplocalcid) for about 10 weeks in the fall, then incorporated later that fall by disking, followed by moldboard plowing. In early May of the following year, sugarbeet were planted, irrigated, then harvested for yield and quality. In the spring and fall of each sugarbeet growing season, soil samples were collected from two depths, 0 to 5 and 5 to 50 mm, on which we measured aggregate stability and size distribution by wet sieving. Soil cores were collected from 0 to 34 mm to measure bulk density. Also in spring and fall, we used ponded and tension infiltrometers placed in the row to measure steady-state, unconfined infiltration rates and, from those rates, to

calculate near-surface hydraulic conductivities at each supply potential. Radish had either few or inconsistent effects on soil structure or hydraulic properties at potentials ≥ -40 mm H_2O. There were, however, two exceptions. Fall-incorporated radish increased the field-saturated water content by 10% to 0.446 m^3 m^{-3} in spring 2003 but had no effect in spring 2004, compared to the control (no oilseed radish). Most importantly, compared to the control, radish as a fall-incorporated green manure consistently increased the proportion of flow-conducting soil pores ≤ 0.75 mm in diameter, likely increasing water retention.

Additional key words: *Raphanus sativus*, cover crop, *Beta vulgaris*, aggregate stability, infiltration rate, hydraulic conductivity

Water use efficiency is increased by improving soil water relations, such as infiltration or water retention, for crops grown in rotation. Adding oilseed radish (*Raphanus sativus* spp. *oleifera*) as a temperate-region, non-legume green manure into crop rotations with barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), and/or sugarbeet (*Beta vulgaris* L.) may enhance soil water relations.

Green manures are crops that, while still green or soon after maturity, are incorporated into soil to improve the soil's physical, chemical, or biological properties and thereby increase the succeeding crop's yield, quality, or both (Cherr et al., 2006). Additions of organic matter, including that from an incorporated green manure, are commonly thought to increase soil organic carbon, aggregate stability, infiltration, and hydraulic conductivity (Martens and Frankenberger, 1992). Amendments can also reduce bulk density, alter soil pore size distributions, reduce a soil's susceptibility to erosion, and slow the formation of surface seals and crusts, thereby maintaining infiltration rates and thus delaying runoff (Bresson et al., 2001; Edmeades, 2003; Haynes & Naidu, 1998). Organic amendment effects on a soil's water-holding capacity (WHC) may or may not occur (Głąb and Kulig, 2008; MacRae and Mehuys, 1985). Adding organic matter may increase both the field capacity and permanent wilting point, resulting in little or no net change (Haynes & Naidu, 1998). Alternatively, such additions may decrease WHC, due to decreases in bulk density and changes in pore size distributions that increase a soil's air-filled porosity (Bauer and Black, 1992). Green manures, including many of their benefits and potential, were reviewed by Cherr et al. (2006) and MacRae and Mehuys (1985). Green manures may also reduce disease incidence by decreasing fall soil water contents to lessen the likelihood of saturated or near-saturated soil the following spring. Soil-borne diseases occur more frequently in wetter than drier soil (Büttner et al., 2002; Rush et al., 2006).

Each year, sugarbeet (*Beta vulgaris* L.) is grown on about 89,000 ha, with yields averaging about 60 Mg ha^{-1}, in the Pacific Northwest states of Idaho, Oregon and Washington, though mostly in Idaho. Two soil-borne diseases of sugarbeet, rhizomania and Rhizoctonia root and crown rot, cause significant losses each year.

Rhizomania, caused by beet necrotic yellow vein virus and vectored by the zoosporic soil fungus *Polymyxa betae*, is considered the most serious disease of sugarbeet worldwide. The disease is a major concern of growers in production areas throughout the United States (Rush et al., 2006) and is estimated to now infest more than 95% of the area used to grow sugarbeet in Idaho, eastern Oregon, and Washington (D. Searle, 2009, personal communication). Resistance to rhizomania is incomplete and long rotations in combination with resistant cultivars and other management practices are necessary to minimize loss (Rush et al., 2006).

Rhizoctonia root and crown rot caused by the soil fungus *Rhizoctonia solani* causes major losses in sugarbeet and occurs wherever the crop is grown (Büttner et al., 2002). An estimated two percent of yield is lost to this disease annually with 30 to 50 percent loss occurring in some fields some years (D. Searle, 2009, personal communication). Growers seldom use *Rhizoctonia*-resistant cultivars because they have 1) only moderate resistance to *Rhizoctonia solani*, 2) even less resistance to more prevalent curly top disease viruses (*Curtovirus* spp.), and 3) lower yield and quality than standard cultivars grown under disease-free conditions.

Oilseed radish is used by sugarbeet growers in the Northwest as a green manure trap crop primarily to reduce populations of sugarbeet cyst nematode, *Heterodera schachtii* or SBCN (Hafez, 1998; Hafez and Sundararaj, 2000). Typically, radish is planted in late summer or early fall following grain, grown with irrigation for six to eight weeks, then incorporated into the soil in late fall by disking, then moldboard plowing. Sugarbeet is planted the following spring (Hafez, 1998). The authors are aware of no reports of any relationship between SBCN and either Rhizoctonia or rhizomania. Surprisingly, however, oilseed radish incorporated earlier as a green manure has been observed to reduce Rhizoctonia root and crown rot in sugarbeet growing in several producer fields not impacted by SBCN. The magnitude of these reductions, however, has not been measured. In preliminary experiments, sugarbeet yield loss from rhizomania, compared to the control, has been reduced more than 20% where oilseed radish had been incorporated the preceding fall. When potato is grown in the rotation, sugarbeet is commonly grown following potato. Some potato growers who plant radish as a green manure in the fall prior to planting potato the following spring, claim disease reduction and yield improvement, due to some unidentified cause, in the potato as well as in the subsequent sugarbeet.

Planting oilseed radish as a green manure appears to reduce the incidence and/or severity of soil-borne diseases of sugarbeet. We do not know, however, whether the often-observed disease-controlling benefits of radish are due directly to pathogen suppression or indirectly to improved soil physical properties and water relations, specifically infiltration rates and hydraulic conductivities. Tension and ponded infiltrometers can be used effectively with software to characterize these hydraulic properties (Ankeny et al., 1993; Hussen and Warrick, 1995; Prieksat et al., 1994). A tension infiltrometer, in essence, holds water within it, releasing the water only when the soil's attraction for the water overcomes the force with which the infiltrometer holds the water, that force being termed the device's water supply potential. Tension infiltrometers supply water to the soil surface at a slightly negative supply potential, often from -20 to -150 mm of water. These negative potentials eliminate flow through large soil pores but permit it through smaller pores in the soil matrix. With tension infiltrometers, one frequently uses ponded infiltrometers to obtain an estimate of the infiltration rate and field-saturated hydraulic conductivity when a very shallow depth of water is ponded on the soil surface.

Some have studied the effects of cover crops, including oilseed radish, on subsequent sugarbeet stand establishment, indicative of surface soil physical properties. In a northwestern Wyoming study, oilseed radish affected neither sugarbeet stands (implying no reduction in crusting) nor the incidence of sugarbeet diseases (Koch and Gray, 1997). Similarly, Allison et al. (1998), in a review of 17 studies conducted in England, found that cover crops did not affect sugarbeet plant populations.

While effects of fall-incorporated radish on the following year's sugarbeet stands and yield are mixed (Koch and Gray, 1997; Krall et al., 1996), radish effects on sugarbeet cyst nematode are not (Hafez and Sundararaj, 2000; Koch and Gray, 1997). The radish stimulates nematode egg hatching and root invasion but hinders cyst development, thereby reducing nematode population density for succeeding sugarbeet. Depending upon the length of the fall growing season for the radish, nematode populations can be reduced by 75% or more. Moreover, planting radish in the early fall after small grain harvest was less expensive (by \$223 ha^{-1}) than purchasing and applying a nematicide to control SBCN (Held et al., 2000).

Oilseed radish in a sugarbeet rotation controls SBCN and likely reduces yield losses from rhizomania and possibly Rhizoctonia. Radish effects, if any, on soil physical and hydraulic properties during the following sugarbeet cropping season are not known. Overall, our project sought to determine the effects of oilseed radish as a green manure crop in sugarbeet cropping systems on 1) sugarbeet disease management, 2) nutrient cycling, and 3) soil microbial populations. The purpose of this field portion of our project was to determine oilseed radish effects on near-surface soil physical and hydraulic properties during sugarbeet cropping seasons at a sprinkler-irrigated site.

MATERIALS AND METHODS

The site was at 42° 35' N, 114° 28' W in Twin Falls, ID. The experimental design was a randomized complete block with six replicates of two treatments, one being oilseed radish as a green manure and the other a control of no oilseed radish. The experiment was conducted from fall 2002 through fall 2004 on a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid), in a field that had been planted to small grain in 2001. The Portneuf's Ap horizon contained about 220 g clay kg^{-1}, 560 g silt kg^{-1}, and about 9.3 g organic C kg^{-1}. The Portneuf had a saturated paste pH of 7.7, calcium carbonate equivalent of about 75 g kg^{-1}, and sodium adsorption ratio (SAR) of 0.87. The soil exhibited little shrinking or swelling but was quite susceptible to structural breakdown, having little organic matter and surface aggregates that fractured readily with only moderate energy input (Lehrsch and Kincaid, 2001; Lehrsch et al., 1991). Neither SBCN nor sugarbeet root knot nematodes (*Meloidogyne* spp.) were found in recent assays of the soil. Malt barley (Coors[1] cv. Moravian 37) was harvested on 1 August 2002 and the straw chopped. We broadcast-applied 56 kg N ha^{-1} (as urea) to the entire site, then incorporated it and the barley straw to a depth of 0.1 m by disking three times. Thereafter, we used a grain drill and packer to seed 'Colonel' oilseed radish at a rate of 28 kg ha^{-1} at the 25-mm depth with a 0.18-m row spacing in all treated plots on 21 August 2002. All plots were 10 x 24 m. Hand-lines were then

[1] Manufacturer or trade names are included for the readers' benefit. The USDA-ARS neither endorses nor recommends such products.

used to sprinkler-irrigate the entire site four times, once about every nine days, applying about 70 mm of water (in gross) at each irrigation. The irrigation water, withdrawn from the Snake River and distributed via canals and laterals, commonly has a pH of 8.2, an electrical conductivity (EC) of 0.5 dS m^{-1}, and an SAR of 0.65. After collecting above-ground biomass from 1 x 1 m areas in late October 2002, we incorporated the radish (approximately 13 Mg ha^{-1} of wet, above-ground plant material) in mid-November 2002 by disking twice, once in each of two diagonal directions, to a depth of 0.1 m, then moldboard plowing to a depth of 0.18 m, and roller-harrowing to a depth of 65 mm. Both the treated and control plots were tilled at the same time and in an identical manner. Early the following spring, the field was disked to 0.1 m, then roller-harrowed to 65 mm. In early May 2003, the field was planted to sugarbeet (Beta[1] cv. 4490 R) at a row spacing of 0.56 m. We irrigated the sugarbeet as needed in amounts sufficient to replace evapotranspiration estimated using AgriMet (Palmer, 2008). To irrigate, we used hand-lines with 3.6-mm-nozzled impact-type heads on 0.9-m risers, positioned every 12.2 m on the lateral. Application intensity was about 6.4 mm h^{-1} and the irrigation duration varied, though it was often 12 h. Final stands (not reported) were measured in all treatments. Insects and weeds were controlled using standard cultural practices recommended by the University of Idaho (Gallian, 2007). At season's end, the sugarbeet was harvested for yield and quality (not reported in this paper). In an adjacent area of the field during this same cropping year, barley, followed in the fall by radish, were grown and irrigated using the same practices as were used the preceding year. After sampling the radish, both the treated and control plots were tilled that fall as they were the preceding year, thus providing the plot area needed for sugarbeet in the succeeding year.

Field measurements and sampling occurred in each sugarbeet cropping year in the spring, on 29-30 May 2003 and 26-27 May 2004, and in the fall, 19-21 Aug. 2003 and 27 Sept. 2004. At each of those four times, soil hydraulic properties were measured *in situ* and soil samples were collected to determine physical properties. Tension infiltrometers (Ankeny, 1992; Hussen & Warrick, 1995) with 0.11-m-diameter bases were used to measure unconfined (three-dimensional), steady-state infiltration rates. At one representative location in the row in each plot, tension infiltration was measured through a 0.115-m diameter, sand-filled ring using a slight modification of the procedure outlined by Ankeny (1992). Infiltration was measured without disturbing the soil surface and from a pre-calibrated, small to large water potential (-40 to -20 mm, or from -0.4 to -0.2 kPa). After the infiltration rate at each potential had stabilized, we manually recorded the elevation of the water surface in the infiltrometer's supply reservoir at intervals of 30 s, then 60 s, until steady-state conditions occurred, commonly 12 to 15 min after infiltration commenced.

Immediately after measuring tension infiltration at a supply potential of -20 mm, ponded infiltration was measured using the equipment and procedure described by Prieksat et al. (1994). Briefly, we first removed the tension infiltrometer, then the wet cheesecloth, with the sand atop it, from within the 115-mm ring. We then placed a dry portion of cheesecloth on the infiltration surface and positioned the ponded infiltrometer above the ring. We lowered the infiltrometer to within 2 to 3 mm of the soil surface, plumbed it, then opened a valve, initiating water flow. After establishing an approximate +5 mm head of water in the ring, we manually recorded water surface elevations in the ponded infiltrometer as we did for the tension infiltrometers. Software described by Ankeny et al. (1993) was used to determine steady-state infiltration rates at each of the three supply potentials, and from them, to calculate hydraulic conductivities.

Soon after measuring ponded infiltration, we moved the infiltrometer from the site and waited until the ponded water still in the ring infiltrated. Immediately thereafter, we collected a gravimetric soil sample from the wetted bulb of soil just beneath the containment ring, sealed the wet soil in a sample can, and transported it to the lab. There, its gravimetric water content was determined. Also in each plot near where tension infiltration was measured, we obtained three volumetric soil samples from the 0 to 34 mm depth in the row on which we later measured bulk density and initial volumetric water content. The wetted bulb sample's gravimetric water content was converted to volumetric water content (hereafter termed field-saturated water content) using the mean surface bulk density measured on the three volumetric samples taken when infiltration was measured (Thony et al., 1991).

We also determined aggregate stability and water-stable aggregate size distribution in the spring and fall when we measured infiltration. We collected two soil samples, of about 25 g each, one from the 0- to 5-mm depth and a second from the 5- to 50-mm depth, from undisturbed soil in the row at two locations in each plot using a small spatula. Upon collection, the samples were composited by depth for each plot. We determined gravimetric water content on a subsample of each, then stored the remaining field moist soil in an air-tight container at +6° C for further analysis. Aggregate stability of these samples was measured using the procedure of Nimmo and Perkins (2002), modified by Lehrsch et al. (1991) to use field-moist 1- to 4-mm aggregates, rather than air-dry

1- to 2-mm aggregates. Those aggregates were slowly wetted to a water content of 0.30 kg kg^{-1} with a cool aerosol produced by a non-heating vaporizer (Humidifier Model No. 240, Hankscraft[1], Reedsburg, WI) just prior to being sieved in reverse-osmosis water (pH of 5.7, EC of 7.2 x 10^{-3} dS m^{-1}, and SAR of 2.2). Aggregate stability was reported as the weight-percent of aggregates that remained stable atop a 0.25-mm sieve after being sieved for 180 s. We also measured the water-stable aggregate size distribution of the soil samples using the procedure of Nimmo and Perkins (2002), modified so that duplicate, 25-g samples of field-moist aggregates that passed an 8-mm sieve were slowly aerosol-wetted to 0.30 kg kg^{-1}. Immediately thereafter, each duplicate was sieved for 600 s in tap water through a nest of sieves with openings of 4.75, 2.0, 1.0, and 0.25 mm. The tap water had a pH of 7.6, EC of 0.7 dS m^{-1} and SAR of 1.7 (Lehrsch et al., 2005). Each resulting size distribution was expressed as a mean weight diameter, MWD (van Bavel, 1949), calculated per Angers and Mehuys (1993), with each sample's duplicate MWDs arithmetically averaged before analysis.

We used SAS (SAS Institute Inc., 2008)[1] to perform a multi-year analysis of variance (ANOVA) using mixed-model procedures and a significance probability (*P*) of 5%, unless otherwise noted. We first examined each response variable's error variance by treatment using the relationship between the variable's treatment means and corresponding treatment standard deviations (Steel and Torrie, 1960). Where necessary, we used a logarithmic or reciprocal square root transformation to stabilize the variable's error variance prior to performing the ANOVA. For the response variables measured at only one depth, the experimental design was a randomized complete block with two treatments (control or treated) and six replications. For those variables, the ANOVA's fixed effects were year, season, treatment, and their interactions. For aggregate stability and MWD (each measured at two depths), the experimental design was a split plot with main plots (control and treated) arranged in a randomized complete block, and subplots being sampling depths, either 0 to 5 or 5 to 50 mm. For these two variables, the ANOVA's fixed effects were year, season, treatment, depth, and their interactions. In the ANOVA for aggregate stability, we used soil gravimetric water content measured at soil sampling as a covariate to account for water content effects on aggregate stability. We separated least-squares means using *t*-tests of pairwise differences at P=0.05. Where needed, means were back-transformed into original units for presentation.

RESULTS AND DISCUSSION

Radish Effects on Soil Structure

Soil structure was little affected by fall-incorporated oilseed radish. Even when soil structure responded to radish treatment, its response was seldom consistent from one year to the next. Variation in aggregate stability was a consequence of differences in gravimetric water content at aggregate sampling. When aggregates were collected, gravimetric water contents averaged across years in the spring at 0 to 5 mm ranged from 0.016 to 0.063 Mg Mg^{-1} and averaged 0.036 Mg Mg^{-1}, while at 5 to 50 mm they ranged from 0.115 to 0.165 Mg Mg^{-1} and averaged 0.135 Mg Mg^{-1}. In contrast, gravimetric water contents varied little by depth in the fall. Across both depths, they ranged from 0.209 to 0.297 Mg Mg^{-1} and averaged 0.238 Mg Mg^{-1}. When gravimetric water content at sampling was used as a covariate to account for this variation, aggregate stability was affected by an interaction between treatment and season (Table 1). When averaged across years and sampling depths, aggregate stability in the spring was slightly greater, though not significantly different at P=0.05, in treated than control soil. Dapaah and Vyn (1998) also reported that spring aggregate stability was greater following a cover crop of oilseed radish compared to following no cover crop. The treated plots' radish biomass, containing relatively little C and much N, likely stimulated microbial activity in early spring to spur such structural improvement (Dapaah and Vyn, 1998; Lynch and Bragg, 1985). This beneficial trend for radish to increase aggregate stability in

Table 1. Oilseed radish treatment effects on aggregate stability in spring and fall at Twin Falls, ID. Data have been averaged across years and sampling depths.

	Aggregate stability†	
Treatment‡	Spring	Fall
	------------ % ------------	
Control	56 (5.1) b§	75 (4.8) a
Treated	58 (5.0) a	72 (5.3) a

† Each mean (n=24) is shown with its standard error in parentheses.

‡ Oilseed radish treatment did not affect aggregate stability (at P=0.05) in either spring or fall.

§ Within a row, means followed by a common letter are not significantly different according to t-tests of pairwise differences at P=0.05.

the spring was not sustained, however, through the fall, likely because of the rapid decomposition of the radish biomass that occurred as the growing season progressed (J. Ellsworth, 2005, personal communication). Treatment differences within season nonetheless were small, particularly when compared to the reported standard errors. Data in Table 1 clearly reveal, however, the increase in Portneuf silt loam aggregate stability that commonly occurs from spring to fall (Bullock et al., 1988; Lehrsch and Jolley, 1992). In our study, the increase in stability from spring to fall was significant for the control but not for the treated soil. Microbial action, increased by the radish green manure, may have quickly increased the stability of treated aggregates in early spring prior to the first sampling in late May of each year. Thereafter, treated plot aggregate stability may have increased at a relatively slow rate from the spring sampling to the fall sampling (Lehrsch and Jolley, 1992). In contrast, the stability of control aggregates may have increased steadily from spring, through summer, into fall, thereby accounting for the larger (and significant) difference in stability from spring to fall (Table 1).

Though not affected by radish treatment, aggregate stability also responded to an interaction between season and sampling depth that was consistent across years (Fig. 1). From spring to fall, aggregate stability

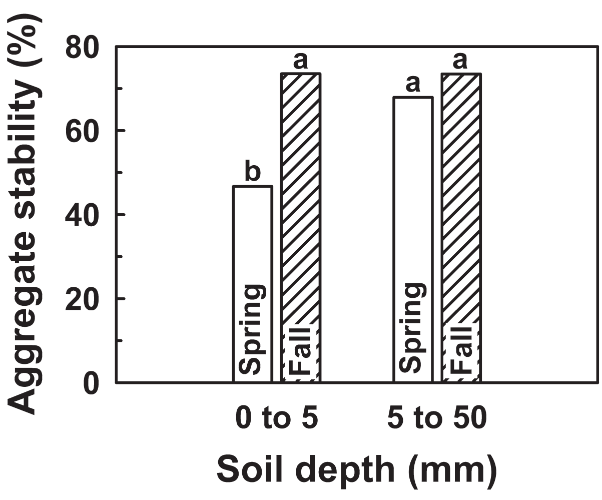

Fig 1. Aggregate stability as a function of soil depth in spring and fall at Twin Falls, ID. Data have been averaged across years and treatments. Within a depth increment, means with a common letter are not significantly different at P=0.05 according to a t-test of pairwise differences.

near the soil surface increased more than half. This increase was likely due to irrigation-caused wetting followed by drying that precipitated slightly soluble bonding agents at contact points within aggregates, strengthening them (Caron et al., 1992; Kemper et al., 1987; Lehrsch et al., 1993). While wetting and drying cycles would have occurred deeper in the soil profile, their extent and frequency would have been greater near the surface than at depth. The substantial stability increase near the soil surface (Fig. 1) could also have been caused, in part, by microbial production of polysaccharides and other organic exudates (Lynch and Bragg, 1985). Microbes would have produced these compounds during the growing season while decomposing organic substrate provided by sugarbeet root sloughing, previous crop residues, or labile organic matter.

Oilseed radish did not affect the Portneuf silt loam's water-stable aggregate size distribution, measured as MWD. When averaged across treatments and depths, however, MWD decreased in 2003 from 1.45 mm in the spring to 0.99 mm in the fall (P<0.001) and in 2004 from 1.12 mm in the spring to 0.98 mm in the fall (NS). These decreases in MWD from spring to fall are somewhat surprising, given the spring to fall increases in aggregate stability that occurred for both treatments (Table 1). As summer progressed, repeated cultivation may have fractured larger but weaker aggregates to yield smaller but more stable aggregates, thus reducing MWD but increasing aggregate stability. This fracturing process or other temporal responses of Portneuf aggregates greater than and/or smaller than those analyzed for aggregate stability may have accounted for this surprising finding (Lehrsch and Kincaid, 2006). Also, the measurement of MWD, compared to stability, subjects aggregates to greater disruptive forces (Nimmo and Perkins, 2002). When averaged across years, seasons, and treatments, MWD at 0 to 5 mm was 1.07 mm, significantly less (P<0.033) than the 1.21 mm at 5 to 50 mm. Tillage, cultivation, early-season sprinkler droplet kinetic energy, repeated freezing and thawing, or any combination of these or other factors could have accounted for MWD, or other measures of soil structure, being less near the surface than at depth (Bullock et al., 1988; Lehrsch, 1998; Lehrsch and Kincaid, 2006).

Oilseed radish affected neither bulk density nor initial volumetric water content, each measured in the uppermost 34 mm of the profile when infiltration was measured. Bulk density was 1.16 Mg m^{-3}, averaged across years, seasons, and treatments. Initial soil water content, averaged across years and treatments, was 0.151 m^3 m^{-3} in the spring, significantly less (P<0.039) than the 0.172 m^3 m^{-3} in the fall. Evaporation in early spring, prior to soil sampling in late May of each year, was likely responsible for water contents being less in spring than fall.

As noted in the Materials and Methods, a disturbed sample was collected in each plot from the saturated bulb of soil beneath the ponded infiltrometer's base immediately after infiltration was measured. This sample's gravimetric water content was subsequently converted to volumetric water content using the mean of the three bulk densities measured nearby. The latter water contents, hereafter referred to as field-saturated water contents, were affected by an interaction between year, season, and treatment (Table 2). In spring 2003, field-saturated soil in the radish-treated plots contained 10% more water (significant at $P<0.019$) than the control plots. By the fall of that year, however, soil in both treated and control plots held statistically similar volumes of water when field-saturated. In the spring of the following year, soil in treated plots held similar, rather than greater, volumes of water when saturated. As noted previously, beneficial effects of radish as a green manure were seldom consistent from one year to the next. From spring to fall each year, field-saturated water contents increased significantly in three of four instances (Table 2).

Table 2. Oilseed radish treatment effects on field-saturated water content in spring and fall of 2003 and 2004 at Twin Falls, ID.

Treatment	Field-saturated water content†	
	Spring	Fall
	------------ $m^3\ m^{-3}$ -----------	
	2003	
Control	0.406 b‡ y§	0.476 a x
Treated	0.446 a x	0.447 a x
	2004	
Control	0.388 a y	0.433 a x
Treated	0.385 a y	0.422 a x

† Each mean (n=6) had a standard error of 0.012 $m^3\ m^{-3}$.
‡ Within a column each year, means followed by a common letter (a or b) are not significantly different according to *t*-tests of pairwise differences at P=0.05.
§ Within a row each year, means followed by a common letter (x or y) are not significantly different according to *t*-tests of pairwise differences at P=0.05.

Radish Effects on Hydraulic Properties

Similar to effects on soil structure, radish effects on soil hydraulic properties, specifically infiltration rate and hydraulic conductivity, were seldom detected and seldom consistent across years when detected, with notable exceptions described below. Infiltration rates measured at three supply potentials in the spring and fall of each year are shown in Fig. 2. The soil water potential at which water is supplied to the soil surface determines the upper limit of the pore diameter through which flow occurs (Table 3). Of significant interest is the infiltration rate measured at a supply potential of 0 mm H_2O, being similar to the infiltration rate often measured in the field using traditional devices such as single- or double-ring infiltrometers. At this potential, infiltration occurs through all surface openings, be they surface cracks, worm holes, or matrix pores. From Fig. 2, in spring 2003 the infiltration rate at 0 mm H_2O supply potential (or simply at 0 mm) for treated plots was slightly greater, though not significantly so at P=0.05, than for control

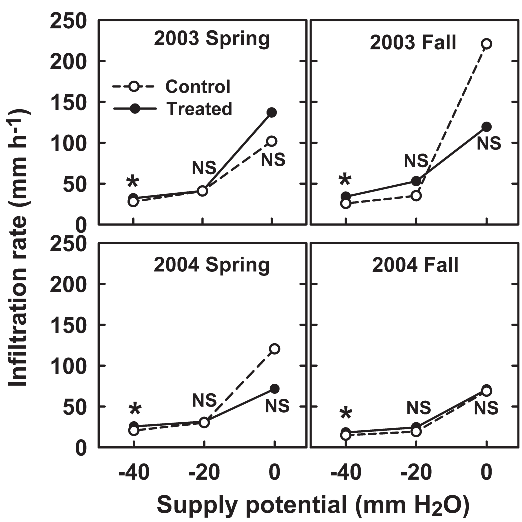

Fig. 2. Infiltration rates at three supply potentials in spring and fall of 2003 and 2004 at Twin Falls, ID. Within each supply potential, each season, and each year, means with NS are not significantly different at P=0.05 while those with * are significantly different at P=0.05 according to a t-test of pairwise differences. A separate ANOVA was performed on transformed data at each supply potential. The infiltration rates shown above have been back-transformed into original units.

plots. Such a ranking was not maintained the following year, however. From spring 2003 to fall 2003, there was a substantial increase in the control's 0-mm infiltration rate, though still not significantly greater than that into treated plots.

At -20 mm, infiltration rates into control and treated plots were similar each season in each year. At -40 mm, in contrast, infiltration rates were greater (P<0.016) into treated than control plots in each season each year. This finding reveals that, compared to the control, fall-incorporated radish increased the proportion of flow-conducting, fine soil pores, those with diameters ≤ 0.75 mm (Table 3), at the soil surface. Głąb and Kulig (2008) also found that incorporated radish biomass increased the soil volume occupied by pores with diameters < 0.5 mm in a silt loam soil (Typic Argiustoll or FAO classed Luvic Chernozem).

Incorporated radish tended to stabilize the infiltration rates at all three supply potentials from spring to fall each year (Fig. 2). While the infiltration rate at 0 mm, for example, into treated plots did not increase with time, neither did it decrease with time, as was noted in 2004 for control plots. Radish treatment may thus sustain infiltration rates later in the season, particularly at higher potentials where most infiltration occurs. Relatively high infiltration rates late in the summer are highly desirable, allowing more water to enter the soil water reservoir to help meet the growing sugarbeet's peaking transpiration demand.

We used the software of Ankeny et al. (1993) with the steady-state infiltration rates of Fig. 2 to calculate the hydraulic conductivities at each of the three supply potentials (Fig. 3). The hydraulic conductivities revealed similar trends as did the infiltration rates in most, but not all, instances. There was a reversal in the ranking of the hydraulic conductivity at 0 mm H_2O supply potential (K_0) for the control and treated plots from spring 2003 to spring 2004, though in neither year were the

Table 3. Relationship between supply potential and maximum pore diameter through which flow occurs (Baver et al., 1972).

Supply potential		Flow occurs through pores with diameters less than or equal to
mm H_2O	kPa	mm
+0	+0	(all pores)
-20	-0.20	1.5
-40	-0.40	0.75

conductivities different. The increase in K_0 for the control from spring to fall of 2003 was sufficient to declare a difference in K_0 between control and treated plots in fall 2003. Unlike for infiltration, the treated plots' K_0 did decrease somewhat from spring to fall 2003. Consistent with the finding from the infiltration rates at -40 mm, hydraulic conductivities at -40 mm were greater (P<0.026) through treated than control plots in both spring and fall of two consecutive years (Fig. 3), revealing a greater proportion of flow-conducting subsurface pores ≤ 0.75 mm in diameter, Table 3. Though the magnitudes of the significant differences in hydraulic conductivities at -40 mm were not great, oilseed radish, incorporated in the fall preceding a sugarbeet crop, clearly increases the number of unobstructed fine soil pores below the soil surface.

The fact that radish increases the proportion of subsurface pores with diameters ≤ 0.75 mm is significant from a water management viewpoint. Pores > 0.75 mm are macropores that drain freely and hold little water against the force of gravity (Timlin et al., 1994; Watson and

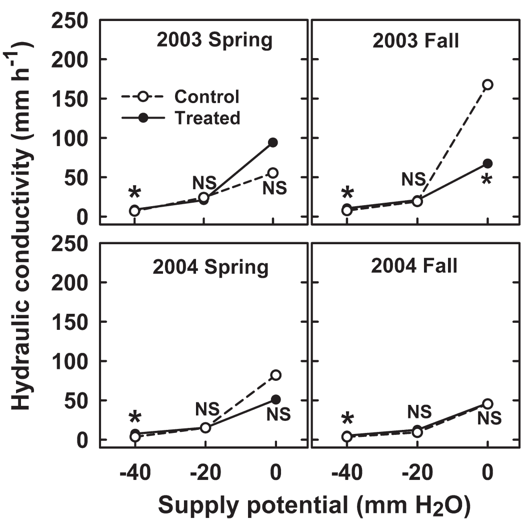

Fig. 3. Hydraulic conductivities at three supply potentials in spring and fall of 2003 and 2004 at Twin Falls, ID. Within each supply potential, each season, and each year, means with NS are not significantly different at P=0.05 while those with * are significantly different at P=0.05 according to a t-test of pairwise differences. A separate ANOVA was performed on transformed data at each supply potential. The hydraulic conductivities shown above have been back-transformed into original units.

Luxmoore, 1986). Pores less than 0.75 mm, at times termed mesopores, better retain water against the pull of gravity but release it slowly to satisfy a growing plant's transpiration demand. In other words, compared to the control, fall-incorporated radish may increase water retention in mesopores throughout the following growing season and therefore increase the water available to support plant growth. Increased available water could account for grower testimonials of enhanced sugarbeet growth and yield following radish. Soils too wet, however, favor soil-borne diseases. Disease incidence and severity are far greater where water is present in macropores compared to mesopores (Rush et al., 2006). Research is currently underway focusing on possible radish effects on soil water retention.

SUMMARY

Fall-incorporated radish did not greatly affect soil physical properties during the following sugarbeet growing season. Compared to the control, radish effects were either not detected or, if detected, were inconsistent from year to year, on aggregate stability, water-stable aggregate size distribution, and bulk density. The field-saturated water content of soil in radish-amended plots, compared to control plots, was 10% greater in spring 2003 and similar in spring 2004. Infiltration rates and hydraulic conductivities at supply potentials ≥ -20 mm H_2O were not affected by radish, in general. Incorporated radish biomass appeared to stabilize both infiltration and hydraulic conductivity from spring to fall, particularly at 0 mm water potential where most water flow occurs. Of greatest significance, radish treatment increased the infiltration rate and hydraulic conductivity through pores ≤ 0.75 mm at and below the soil surface season-long, compared to the control.

ACKNOWLEDGMENTS

Portions of this investigation were funded via Specific Cooperative Agreement No. 58-5368-2-833 between the USDA-ARS and the University of Idaho. The authors thank L. Balis-Cypriano, P. M. Jolley, S. J. McClure, R. M. McNurlin, and P. J. O'Connor for data collection, laboratory analyses, and preliminary data handling, and J. A. Foerster for editing figures.

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